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Spatial heterogeneity of ocean surface boundary conditions under sea ice

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ABSTRACT

The high heterogeneity of sea ice properties implies that its effects on the ocean are spatially variable at horizontal scales as small as a few meters. Previous studies have shown that taking this variability into account in models could be required to simulate adequately mixed layer processes and the upper ocean temperature and salinity structures. Although many advanced sea ice models include a subgrid-scale ice thickness distribution, potentially providing heterogeneous surface boundary conditions, the information is lost in the coupling with a unique ocean grid cell underneath. The present paper provides a thorough examination of boundary conditions at the ocean surface in the NEMO-LIM model, which can be used as a guideline for studies implementing subgrid-scale ocean vertical mixing schemes. Freshwater, salt, solar heat and non-solar heat fluxes are examined, as well as the norm of the surface stress. All of the thermohaline fluxes vary considerably between the open water and ice fractions of grid cells. To a lesser extent, this is also the case for the surface stress. Moreover, the salt fluxes in both hemispheres and the solar heat fluxes in the Arctic show a dependence on the ice thickness category, with more intense fluxes for thinner ice, which promotes further subgrid-scale heterogeneity. Our analysis also points out biases in the simulated open water fraction and in the ice thickness distribution, which should be investigated in more details in order to ensure that the latter is used to the best advantage.

1. Introduction

The presence of sea ice at the polar oceans surface has numerous impacts on their upper layer physics and biogeochemistry. Its high albedo compared to seawater strongly reduces the amount of absorbed solar radiation, giving rise to the well-known positive ice-albedo feedback (Curry et al., 1995). It constitutes an efficient barrier for mass exchanges between the atmosphere and the sea surface, inhibiting evaporation and preventing at least a fraction of precipitation from entering the ocean at the time when it falls. Owing to its low thermal conductivity (Pringle et al., 2007), sea ice dampens the oceanic heat losses to the atmosphere in winter. Because its salinity is lower than that of the sea surface, and because it is transported by winds and currents, its formation and melt are associated with buoyancy fluxes that influence the upper ocean stratification, convective processes and eventually the global thermohaline circulation (e.g., Goosse and Fichefet, 1999). A compact sea ice cover prevents the formation of waves and direct wind-generated turbulence in the water column, but its relative motion with respect to the water is a source of stress at the ocean surface. From a biogeochemical point of view, sea ice modulates the gas exchanges at the atmosphere-ice-ocean interface, provides a support for microbiological activity and chemistry, and acts to concentrate, transport or release nutrients and substances like inorganic carbon (Vancoppenolle et al., 2013).

The sea ice cover is a fundamentally heterogeneous medium. During summer, large open water areas can exist between the melting floes. A few percent of the sea surface remain free of ice even at the core of the winter season, in the form either of linear openings caused by divergence of the pack, known as leads, or of polynyas created by strong winds or high oceanic heat supply. The ice itself is a mixture of components ranging from thin new ice formed in open water areas to ridges several meters thick resulting from deformation inside the pack (Thorndike et al., 1975). While the most substantial differences in surface conditions occur between ice-covered and ice-free areas, several of the processes listed above also depend on the sea ice type, thickness and surface state. As these vary significantly on small horizontal scales, so do their effects on the underlying ocean and the atmosphere above.

It has long been recognized important to represent the subgrid-scale heterogeneity of ice thickness in order to accurately simulate the sea ice evolution (Thorndike et al., 1975; Hibler, 1980). As a

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consequence, ice thickness distributions are included in most advanced models nowadays, among which CICE (Los Alamos Sea Ice Model, Hunke et al., 2015) and PIOMAS (Pan-Arctic Ice-Ocean Modeling and Assimilation System, Zhang and Rothrock, 2003). It allows them to compute the open water fraction and the concentration of ice of various thicknesses based on thermodynamic and dynamic processes. The implementation details and the impacts on model results are likewise intensively studied (e.g., Massonnet et al., 2011; Komuro and Suzuki, 2013; Castro-Morales et al., 2014; Hunke, 2014). However, the spatial heterogeneity in ocean surface boundary conditions implied by this variability in ice properties has been so far overlooked. This is explained by the fact that the various ice thickness categories have to exchange information with a unique ocean grid cell underneath, which requires the fluxes to be aggregated into single values.

Previous studies have shown that taking the surface conditions heterogeneity into account is necessary in order to adequately simulate the ocean physics below sea ice. By comparing vertical mixing parameterizations commonly used in coarse resolution large-scale models with large eddy simulations, (Losch et al., 2006) have demonstrated that neglecting the heterogeneous nature of buoyancy fluxes associated with a partial ice cover leads to biases in the mixed layer depth and the upper ocean density structure. Brine rejection parameterizations have for instance been developed to represent the impacts of intense convective mixing in winter leads (e.g., Duffy and Caldeira, 1997; Nguyen et al., 2009; Barthélemy et al., 2015). Further studies have implemented explicit separate vertical mixing computations in fractions of individual grid cells corresponding to ice and to open water (Holland, 2003; Jin et al., 2015).

Nevertheless, a detailed description of the heterogeneous ocean surface boundary conditions under sea ice is still missing, to our knowledge. The objective of the present paper is therefore to fill in this gap. In addition to leading to a better understanding of the spatial distribution of sea ice-ocean interactions, this will be of great interest to help interpreting the results of the above-mentioned studies. Under-ice observations are still far too sparse to allow examining under-ice fluxes at large scale and in all seasons. Our study will hence make use of the global ocean-sea ice model NEMO-LIM, whose ice component includes a state-of-the-art ice thickness distribution and in which the subgrid-scale heterogeneity of all fluxes and of the stress provided at the ocean surface will be thoroughly investigated.

This paper is organized as follows. The NEMO-LIM model setup is described in Section 2, with a particular emphasis on the ocean surface boundary condition aspects. The modeled mean sea ice state and ice thickness distribution are documented in Section 3, because they constitute the background for the simulation of heterogeneous boundary conditions. The latter are presented and discussed in Section 4. A summary of our findings is finally given in Section 5.

2. Model setup

2.1. Ocean-sea ice model NEMO-LIM

The ocean component of NEMO (Nucleus for European Modelling of the Ocean) is a finite difference, hydrostatic, free surface, primitive equation model fully described in Madec (2008). The ocean model's version 3.5 is coupled to the latest revision of the dynamic-thermodynamic sea ice model LIM (Louvain-la-Neuve sea Ice Model), known as LIM3.6 (Vancoppenolle et al., 2009; Rousset et al., 2015). LIM includes an ice thickness distribution (ITD), which allows to represent the subgrid-scale heterogeneity of ice thickness, enthalpy and salinity. A C-grid formulation of the elastic-viscous-plastic rheology is utilized for ice dynamics (Bouillon et al., 2013). The model configuration is very close to the one used in Barthélemy et al. (2015). Three noticeable differences are listed hereafter, along with details about the ocean surface boundary conditions (SBCs) and the experimental design.

First, compared to Barthélemy et al. (2015), we use a slightly updated version of LIM, in which several minor heat conservation leaks have been fixed (Rousset et al., 2015).

Second, the background diffusivity in the so-called TKE vertical mixing scheme (for turbulent kinetic energy, Blanke and Delecluse, 1993; Madec, 2008) has been lowered in the polar regions, following studies showing that it improves Arctic Ocean simulations (Zhang and Steele, 2007; Nguyen et al., 2009; Komuro, 2014). In practice, a tenfold reduction of the background vertical diffusivity poleward of 60° N and of 60° S is implemented, whereas the reference value (1.2×10^{-5} m/s^2) is maintained between 50° N and 50° S. The transitions between the different sectors are linear. In the Antarctic, results are mostly unaffected because the vertical diffusivity computed by the TKE scheme is nearly always above the default background value. Lowering the latter has therefore almost no impact in this region. Simulated mixed layer depths (MLDs) in the Arctic Ocean are reduced, leading to a better agreement with observations (Barthélemy et al., 2015).

Third, two artificial connections present in the standard version of LIM between the ice-free and ice-covered fractions of grid cells have been removed. Previously, ice was allowed to grow in the ice-free part of a grid cell only if the surface heat loss was large enough as to cool the entire top oceanic cell down to the freezing point. On the other hand, in the melting season, positive surface heat fluxes in open water were not used to increase the temperature of ocean cells in which ice was still present, but were rather transferred to the sea ice base. These two processes provided an instantaneous link between the ice-free and ice-covered parts of grid cells, and complicated the interpretation of ocean surface fluxes in open water and below ice. Their removal leads to smaller open water fractions in winter, but the combined effect on sea ice thickness is weak. The code has been modified so that ice can grow in the ice-free fraction of a grid cell as soon as the heat loss is sufficient to lower the temperature of the corresponding cell fraction to the freezing point, and positive heat fluxes in open water simply increase the sea surface temperature (SST). The impact of the treatment of ice formation in leads has been examined in greater detail in a recent study using the sea ice model CICE (Wilchinsky et al., 2015).

In virtually all large-scale applications since it was introduced in version 3 of LIM, the ITD has been used with five ice thickness categories. The surface of each grid cell is thus separated into six parts. The first one is the ice-free fraction, representing open water and leads within the sea ice cover, and the remaining five correspond to the ice thickness classes, each one having its own concentration. The upper thickness limits for the first four categories are 0.63 m, 1.33 m, 2.25 m and 3.84 m, while the fifth is unbounded. Transfers between the different categories are caused by thermodynamic growth or melt and by the deformation processes that the model accounts for, namely ridging and rafting (Vancoppenolle et al., 2009).

2.2. Ocean surface boundary conditions

Our aim here is examining the subgrid-scale heterogeneity of ocean SBCs associated with the ITD present in LIM. To this end, the surface thermohaline fluxes and the norm of the surface stress have been diagnosed separately for the six fractions of each grid cell.

On the one hand, the thermohaline fluxes are the main drivers of SST and sea surface salinity (SSS) variations, and hence of buoyancy changes at the ocean surface. We will look at the freshwater,